Eclipses and orbital modulations in binary pulsar PSR J0737−3039

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Abstract

Binary radio pulsar system J0737−3039 provides an exceptional opportunity to study innermost structure of pulsar magnetospheres due to very tight orbit, favorable directions of pulsars' rotation and magnetic axes and extremely fortuitous orientation of the orbit. In this system the millisecond pulsar A is eclipsed once per orbit. During eclipse a clear modulation at the 2.77 s period of pulsar B is seen, pointing unambiguously to magnetospheric origin of eclipses. A simple geometric model, based on the idea that the radio pulses are attenuated by synchrotron absorption on the closed magnetic field lines of pulsar B, can successfully reproduces the eclipse light curves down to intricate details. This detailed agreement confirms the dipolar structure of the neutron star's magnetic field. The model gives clear predictions for temporal evolution of eclipse profile due to geodetic precession of pulsar B.

In addition, pulsar B shows orbital modulations of intensity, being especially bright at two short orbital phases. We showed that these modulations are due to distortion of pulsar B magnetosphere by pulsar A wind which produces orbital phase-dependent changes of the direction along which radio waves are emitted. Thus, pulsar B is intrinsically bright at all times but its radiation beam misses the Earth at most orbital phases.

Key words: pulsars: individual (PSR J0737-3039) – stars: neutron

1 Amazing and lucky: double pulsar PSR J0737−3039A/B

The double pulsar system PSR J0737−3039A/B contains a recycled 22.7 ms pulsar (A) in a 2.4 hr orbit around a 2.77 s pulsar (B) (Burgay et al., 2003; Lyne et al., 2004). The system is viewed nearly edge on, with the line of sight making an angle $\sim 0.5°$ with the orbital plane (Cole et al., 2004; Ransom et al., 2004). This leads to a number of exceptional properties of the system. Pulsar A is eclipsed once per orbit, for a duration of ~ 30 s centered around superior conjunction (when pulsar B is between the observer and pulsar A). The width of the eclipse is

only a weak function of the observing frequency (Kaspi et al., 2004). Most surprisingly, during eclipse the pulsar A radio flux is modulated by the rotation of pulsar B: there are narrow, transparent windows in which the flux from pulsar A rises nearly to the unabsorbed level (McLaughlin et al., 2004). These spikes in the radio flux are tied to the rotational phase of pulsar B, and provide key constraints on the geometry of the absorbing plasma. At ingress transparent spikes appear at half rotational period of B, then change their modulation to rotational period of B at the middle of eclipse and disappear completely right before the egress (Fig 1). On average the eclipse is longer when the magnetic axis of pulsar B is approximately aligned with the line of sight (assuming that radio pulses are generated near the magnetic axis of B).

The physical width of the region which causes this periodic modulation is comparable to, or somewhat smaller, than the estimated size of the magnetosphere of pulsar B. Combined with the rotational modulation, this provides a strong hint that the absorption is occurring *within* the magnetosphere of pulsar B. This allows us to probe directly the structure of pulsar B magnetosphere.

We constructed a detailed model of eclipses (Lyutikov & Thompson, 2005) which shows that the light curve is consistent, in considerable detail, with synchrotron absorption in magnetosphere of pulsar B. The agreement is detailed enough to constitute direct evidence for the presence of a *dipolar* magnetic field around pulsar B.

2 Magnetosphere of pulsar B

At distances much larger than neutron star radius but much smaller than light cylinder radius, $R_{LC} \sim c/\Omega$ (Ω is rotation frequency of a pulsar, magnetospheres of *isolated* pulsars are nearly dipolar, containing two types of magnetic field lines: those that close inside R_{LC} and those that cross the light cylinder and thus remain open to infinity (Goldreich & Julian, 1969). Radio emission is, presumably, generated on the open field lines near the neutron star magnetic polar field line.

In case of PSR J0737−3039B this picture is modified by strong interaction of pulsar B with relativistic wind flowing outward from pulsar A. Wind of A strongly distorts B magnetosphere, blowing off a large fraction of it, so that the size of magnetosphere of B facing A is much smaller than light cylinder and is now determined by the pressure balance between the wind of pulsar A and the magnetic pressure of pulsar B (*e.g.* Lyutikov, 2004). Observationally, this is confirmed by the fact that the half-width of the eclipse, $\sim 1.6 \times 10^9$ cm, is much smaller than the pulsar B light cylinder $R_{LC} \sim 1.3 \times 10^{10}$ cm.

As a results of interaction with A wind, spindown torque on pulsar B is modified if compared with the vacuum case. This has important implications for pulsar B magnetic

field and spindown age, which can be estimated self-consistently only by modeling the interaction between wind and magnetosphere (conventional vacuum spindown formulas are incorrect in this case!). Estimates of the torque (Lyutikov, 2004; Arons et al., 2004) show that *breaking index of pulsar B is likely to be close to* 1 and may even approach 0 (instead of vacuum dipole case of 3). Surface magnetic field and magnetospheric radius can be estimated as

$$B_{\mathrm{NS}} \simeq \frac{D_{AB}^{1/2} \left(I_B \dot{\Omega}_B / \Omega_B \right)^{3/4} c}{\left(I_A \Omega_A \dot{\Omega}_A \right)^{1/4} R_{\mathrm{NS}}^3} =$$

$$4 \times 10^{11} \frac{I_{B,45}^{3/4}}{I_{A,45}^{1/4}} \quad \mathrm{G};$$

$$R_{\mathrm{mag}} \simeq \left[\frac{(c D_{AB})^2 I_B \dot{\Omega}_B}{I_A \Omega_A \dot{\Omega}_A \Omega_B} \right]^{1/4} =$$

$$4.0 \times 10^9 \left(\frac{I_B}{I_A} \right)^{1/4} \quad \mathrm{cm} \qquad (1)$$

where $\Omega_{A,B}$ and $\dot{\Omega}_{A,B}$ are measured spin frequencies and frequency derivatives (Burgay et al., 2003), $I_{A,B}$ are moments of inertia normalized to 10^{45} g cm^2 and D_{AB} is distance between pulsars.

As long as parameters of pulsar A remain approximately constant, over time scale of 250 Myrs, pulsar B spins down exponentially, $\Omega_B \propto \exp\{-t/\tau\}$ where $\tau = \Omega_B / \dot{\Omega}_B \approx 100$ Myrs (note that this is two times larger than its characteristic age).

While details of magnetosphere-wind interaction are bound to be complicated, a reasonable guess, on which

the above estimates are based, is that open-field current density remains similar to the one in isolated pulsars, $j \sim n_{GJ} e c$ ($n_{GJ} = \Omega B / 2\pi e c$ is Goldreich-Julian density), while the size of open field lines is increased due to smaller size of B magnetosphere. In fact, field dragging at the magnetospheric boundary may increase typical current density deep inside magnetospheres. This will lead to increased torque and decreased estimates of surface magnetic field and magnetospheric radius. Still, we can estimate the minimum magnetospheric radius by assuming that at the boundary toroidal magnetic field does not exceed poloidal magnetic field. This gives a minimum estimate of the magnetospheric radius (corresponding to spindown index 0): $R_{\mathrm{mag,min}} = \left(\frac{I_B \dot{\Omega}_B}{I_A \Omega_A \dot{\Omega}_A} \right)^{1/3} \left(\frac{c D_{AB}^2}{2} \right)^{1/3} = 2.4 \times 10^9$cm. Note, that this is still somewhat larger than the size of eclipses.

2.1 Model of eclipses

Similar to the case of isolated pulsars, we assume that magnetic fields lines of pulsar B are of two types: open and closed ones. In addition, we assume that closed magnetic fields lines extend not up to the light cylinder but up to the magnetosphere radius R_{mag}, while field lines extending further than R_{mag} remain open. We place the absorbing relativistically hot plasma within a set of closed dipolar field lines. It can be shown that plasma density is constant along each field line. We further assume

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that density and temperature do not vary *between* field lines. Both of these assumptions have only minor effect on eclipse profile.

We calculate the synchrotron optical depth over a large number of lines of sight, taking into account both the three-dimensional structure and rotation of B magnetosphere (Fig. 2). The calculation of the eclipse light curve requires a choice of several parameters: direction of rotational axis (angles θ_Ω, ϕ_Ω), angle between rotational and magnetic axis χ, impact parameter z_0, electron temperature T_e, density multiplicity λ_{mag} (ratio of density to Goldreich-Julian density) and outer radii $R_{\mathrm{abs}+}$

Results of the simulations are compared with data on in Fig. (1) *The model reproduces many fine details of the eclipses.* The model can reproduce asymmetric form of eclipse with the ingress shallower and longer than the egress. It explains the modulation of that is observed at the first and second harmonics of the spin frequency of pulsar B, and the deepening of the eclipse after superior conjunction. The average eclipse duration is almost independent of frequency when multiplicity is sufficiently large. The onset and termination of the eclipse are determined mostly by the physical boundary of the absorbing plasma and not by microphysics of absorption process. This results in nearly frequency independent eclipses. Eclipse is broader when the magnetic moment of pulsar B is pointing closest to the observer, just as is observed (McLaughlin et al., 2004). There

are modest deviations between the model and the data near the edges of the eclipse that could be used to probe the distortion of magnetic field lines from a true dipole.

The modulation of the radio flux during the eclipse is due to the fact that – at some rotational phases of pulsar B – the line of sight only passes through open magnetic field lines where absorption is assumed to be negligible. One of the main successes of the model is its ability to reproduce both the single and double periodicities of these transparent windows, at appropriate places in the eclipse. This requires that $\vec{\mu}_B$ be approximately – but not quite – orthogonal to $\mathbf{\Omega}_B$.

Based on a sample of many eclipse light curves our best fit parameters are: $z_0 \simeq -7.5 \times 10^8$ cm, $\theta_\Omega \simeq 60°$, $\phi_\Omega \simeq -90°$, $\chi \simeq 75°$. The orbital inclination is therefore predicted to be close to 90.55°, (*cf.* Cole et al., 2004; Ransom et al., 2004). The size of the eclipsing region is $R_{\mathrm{abs}+} = 1.5 \times 10^9$; the implied multiplicity is large, $\lambda_{\mathrm{mag}} = n_{mag}/n_{GJ} \sim 10^5$. Lorentz factor of suspended plasma was fixed at $\gamma = 10$ (there is a degeneracy between Lorentz factor and density).

Presence of high multiplicity, relativistically hot plasma on closed field lines of pulsar B is somewhat surprising, but not unreasonable. Dense, relativistically hot plasma can be effectively stored in the outer magnetosphere, where cyclotron cooling is slow. The gradual loss of particles inward through the cooling radius, occurring on time scale of millions of

pulsar B periods, can be easily compensated by a relatively weak upward flux driven by a fluctuating component of the current. For example, if suspended material is resupplied at a rate of one Goldreich-Julina density per B period and particle residence time is million periods, equilibrium density will be as high as $10^6 n_{GJ}$. The trapped particles are also heated to relativistic energies by the damping of magnetospheric turbulence (Lyutikov & Thompson, 2005).

There is only one slight deviation from simple estimates: our eclipse calculations show that the optical depth of the absorbing plasma undergoes a sharp drop at a distance $R_{\mathrm{abs}+} \simeq 1.5 \times 10^9$ cm from pulsar B. This is about 2.5 times smaller than the expected radius of the magnetopause, $R_{\mathrm{mag}} \simeq 4 \times 10^{10}$ cm. Most likely this is due to the loss of plasma from the outermost closed field lines due to reconnection and/or gradient drift.

2.2 Predictions of the model

There is a number of predictions of the model that should be tested in the coming years.

(1) The spin $\boldsymbol{\Omega}_B$ of pulsar B is expected to undergo geodetic precession on a ~ 75 year timescale (Burgay et al., 2003). We have provided predictions for how the eclipse light curve will vary as a result. In particular, the orbital phase at which the radio flux reaches a minimum will shift back toward superior conjunction. Since ϕ_Ω is not well constrained, a time for eclipse to become symmetric is between ~ 12 years (if $|\phi_\Omega + 90°| \sim 30°$ and $\boldsymbol{\Omega}_B$ is drifting away from the plane of the sky) and ~ 25 years (if ϕ_Ω is drifting toward the plane of the sky).

(2) High time-resolution observations are a sensitive probe of the distribution of plasma properties (density and temperature) on the closed field lines. If plasma is depleted from the outermost field lines, at high temporal resolution the flux should return to unity. On the other hand, if the absorbing plasma does not have a sharp truncation in radius, then the flux will not return to unity in all of the transparent windows.

(3) The eclipses must regain a strong frequency dependence at sufficiently high frequencies. The critical frequency above which significant transmission occurs can be used to place tight constraints on the plasma density. The electron cyclotron frequency at a distance $r \sim z_0 \sim 7.5 \times 10^8$ cm from pulsar B is estimated to be $\nu_{B,e} \sim 3$ GHz. One therefore expects the eclipses to develop a significant frequency dependence at higher frequencies.

(4) There are a number of definite predictions for the polarization of the transmitted radiation (Lyutikov & Thompson, 2005). But since pulsar A emission is strongly polarized one needs to know absolute position of the

direction of linear polarization.

3 Orbital modulation of B due to distortion of B magnetosphere by A wind

Next we turn to orbital modulations of intensity of J0737−3039B. Emission of pulsar B is strongly dependent on orbital phase, being especially bright at two windows, each lasting for about 30° (Lyne et al., 2004). Pulse profiles have different shapes in the two windows. We showed (Lyutikov, 2005) that orbital brighting of B is not intrinsic but is due to distortions of B magnetosphere by pulsar A wind, so that radiating beam of B mostly misses the observer, except at two orbital phases.

To prove this point, we assume that intrinsically bright pulsar B radio emission is generated near the polar field line inside a region with half opening angle of ~ 2 degrees, while the polar field line itself is "pushed around" by the pressure of A wind. To parametrize the effects of A wind on direction of radio emission of B we employ a method of distortion transformation of Euler potentials (Stern, 1994), developed for modeling of the Earth magnetic field influenced by solar wind. Assuming that radio emission of B is generated in physically small region of B magnetosphere (much smaller than its size), direction of radio emission of B can be parametrized by a distortion coefficient C (Lyutikov, 2005) (so that distortion is proportional to $1 - C$, for pure dipole $C = 1$).

To fit the data we use the results of modeling of pulsar A eclipse (Lyutikov & Thompson, 2005). Searching through parameter space we were able to obtains a satisfactory fit, producing emission at two orbital phases nearly coincident with observed ones, Fig. 3.

The strength of the model is that it reproduces (or predicted) fairly well a number of properties of pulsar B radio emission. First, since at different orbital phases the line of sight makes different cuts through emission region, the model naturally explains orbital phase-dependent averaged emission profile. In fact, this can be used to construct a map of the emission region, something which was not possible for isolated pulsars. Secondly, since the emitting beam of B is pointing in somewhat different directions at different orbital phases, time of arrival of pulses of B should experience regular orbital-dependent changes by as much as $\sim (2°/360°)2.8\mathrm{sec} \sim 10$ ms. Such drift in times of arrival has been observed: Ransom et al. (2004) reported a systematic change in arrival times of B pulses by 10-20 ms.

Finally, since emission beam of B is fairly narrow, small changes in the orientation of rotation axis of B may induce large apparent changes in the profile. One possibility for the change in the direction of the spin is geodetic precession of B, which should happen on a relatively short time scale ~ 70 yrs (Lyne et al., 2004). From our modeling we find that changes of ϕ_Ω by as little as $\sim 1°$ strongly affect observed B profile. Thus, we expect that

profile of B may change on a times scale of less than a year. [1] This prediction has been recently confirmed by Burgay et al. (2005), who see evolution of profile of PSR J0737−3039B in general agreement with our model.

Another possible implication of the model concerns emission heights in pulsar B. Data are best fitted by the model with the stretching coefficient $C = 0.7$, so relative deformation of the magnetosphere at the emission radius is $\sim 30\%$. This is a fairly large distortion, which favors large emission altitudes, $R_{em} \geq 10^8$ cm. Large emission altitudes in isolated pulsars have been previously suggested by Lyutikov et al. (1998).

The main implication of the model is that B is always intrinsically bright. Its peak luminosity of ~ 3 mJy at 820MHz is, in fact, typical for isolated pulsars with similar properties. There is a number of ways the model can be improved. First, a better model of dipole distortion is needed. This can be achieved by using well developed models of the Earth magnetosphere: since the size of pulsar B magnetosphere is much smaller than light cylinder, light travel effects are probably unimportant. Second, a non-trivial geometry of the emission region, as opposed to a circular used in the present study, may increase the quality of the fit. Also, if reconnection between wind and magnetospheric field lines is important, the

structure of magnetosphere may depend on the direction of the wind magnetic field. We plan to address these issues in a subsequent paper.

4   Conclusion

The success of the models is somewhat surprising, given the complexity of data and the fact that we had to fit many parameters. The reasons for it is that, to the first order, magnetic field of B is well approximated by dipolar structure. Thus, the models provide a strong test of the long-standing assumption that neutron stars are surrounded by corotating, *dipolar* magnetic fields. This is a valuable confirmation of a fundamental assumption made in models of pulsar electrodynamics. In addition, our results are consistent with models that place the source of the radio emission close to the magnetic axis. Forthcoming improvement of the model should be able to quantify deviations of the magnetosphere from dipolar shape and probe how a pulsar magnetosphere interacts with an external wind.

Our eclipse model is consistent with a large natal kick of pulsar B that changes the orientation of the orbital plane and disrupt any pre-existing alignment between orbit and the spin of the progenitor star.

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[1] According to the model, we are not likely to lose pulsar B in the coming year(s), yet the model is not sufficiently detailed to guarantee it.

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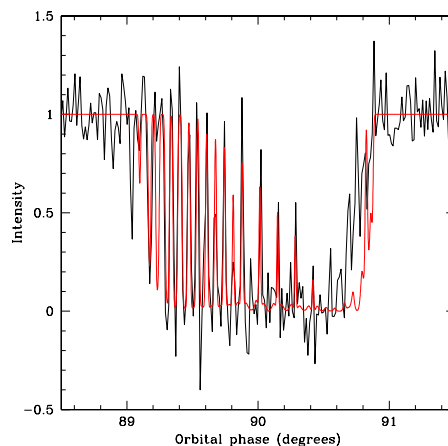Stern, D., 1994, Jour. Geophys. Res., 99, 2443

Fig. 1. Comparison of a simulated eclipse profile with 800 MHz data (McLaughlin et al., 2004). The model fits the data best in the middle of the eclipse.
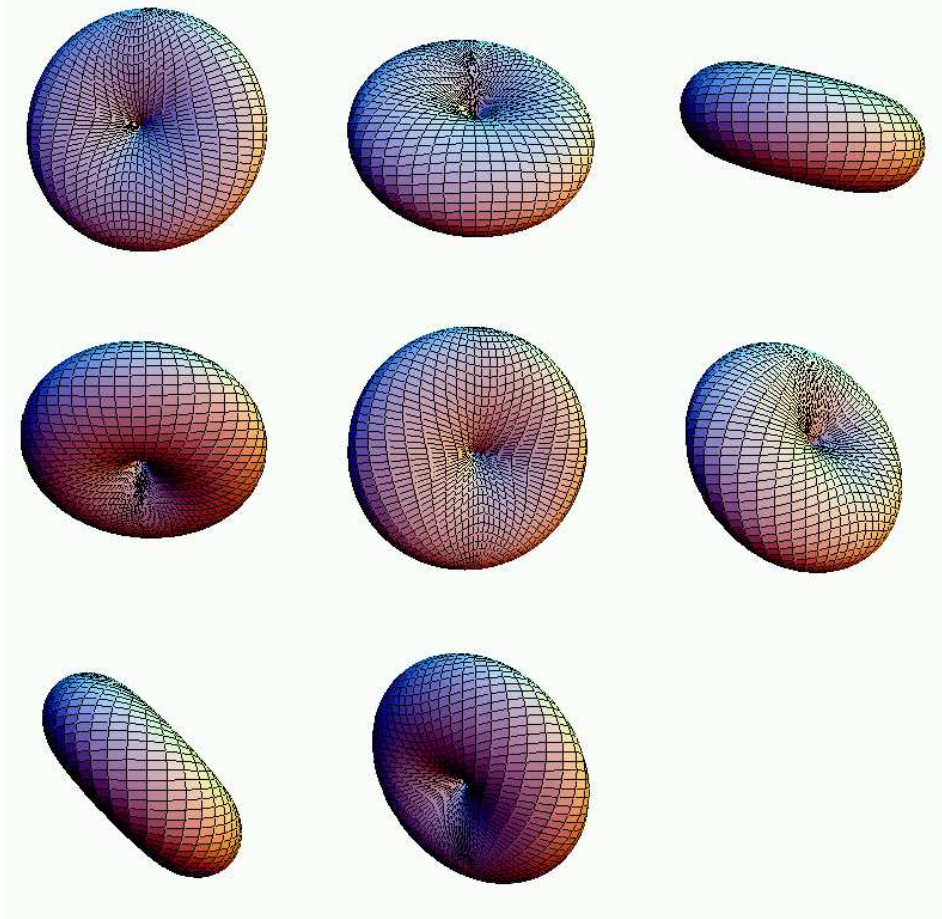
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Fig. 2. View of the magnetosphere at different rotational phases separated by $\pi/4$. For a full movie of the eclipse see http://www.physics.mcgill.ca/∼lyutikov/movie.gif
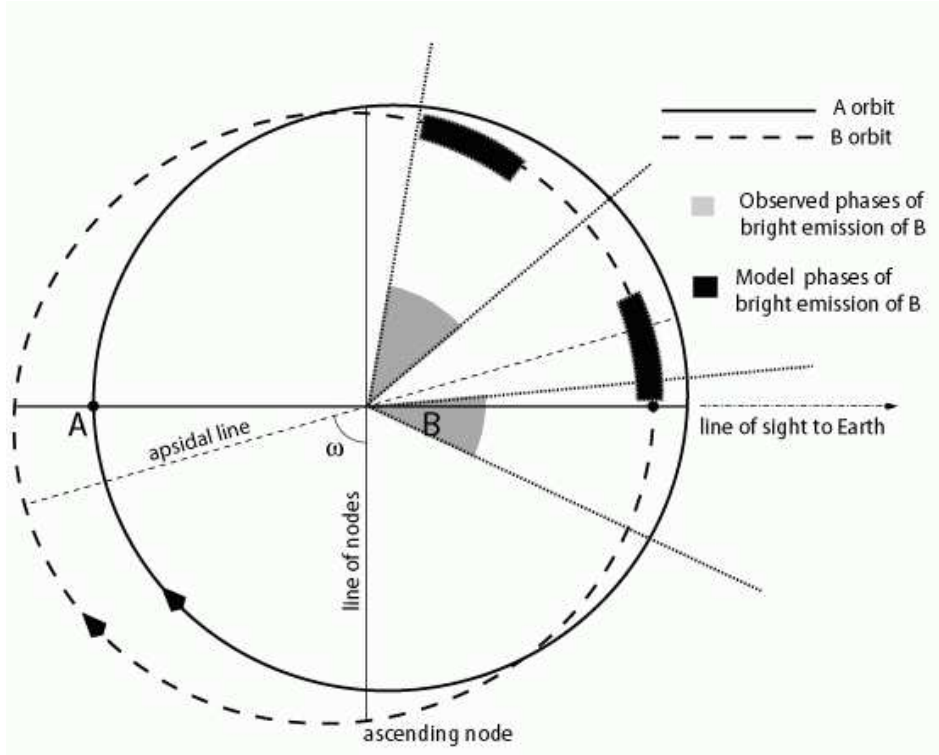
Fig. 3. Configuration of the system, after Lyne et al. (2004). Light shades segments indicate orbital phases where B emission is strongest, dark regions indicate the location of emission in our best fit model.